

Intelligent Extruder for Polymer Compounding

GE Industrial Systems Solutions

GE Global Research Center

Coperian Werner-Pfleiderer Corporation USA

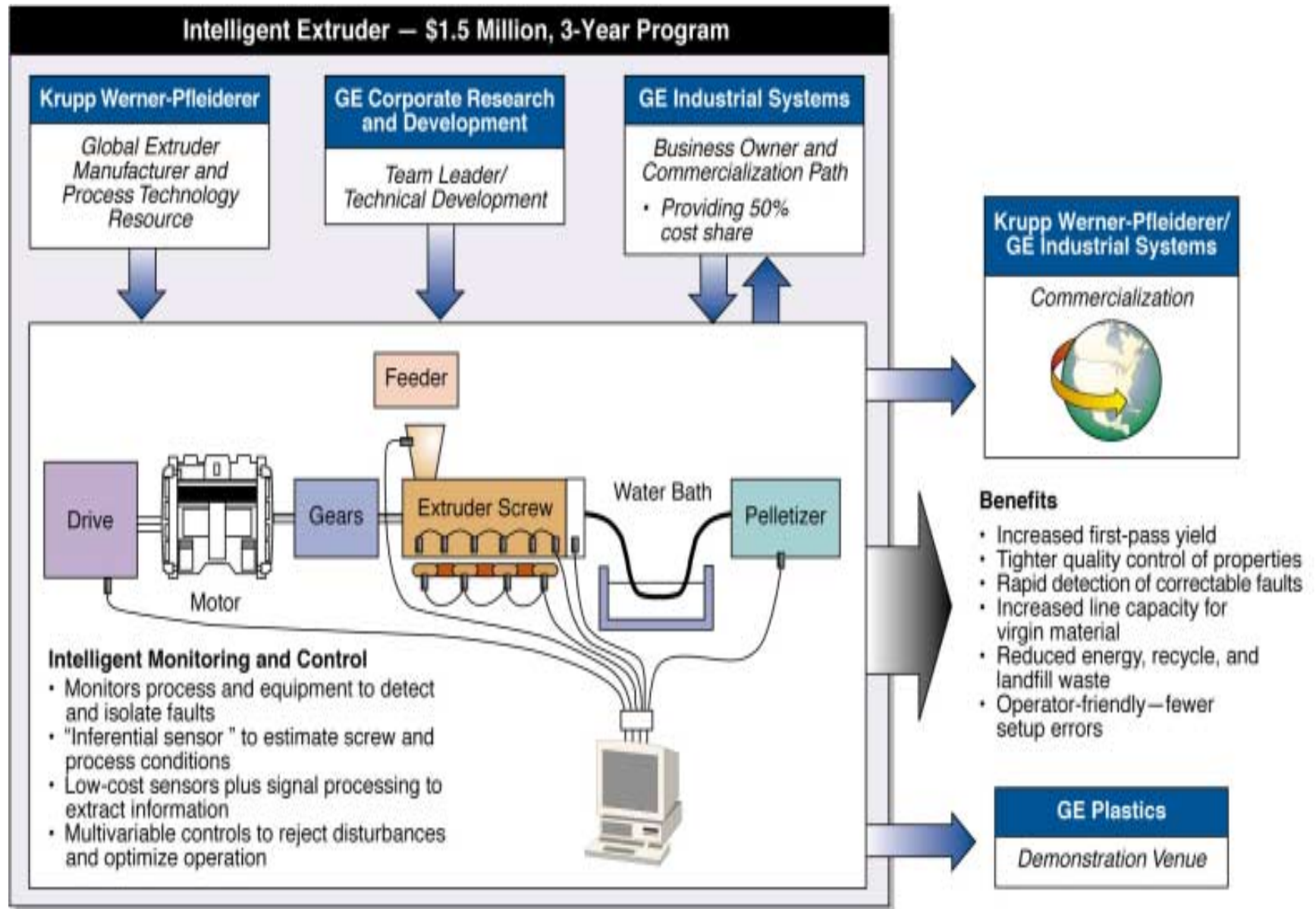
US Department of Energy / OIT



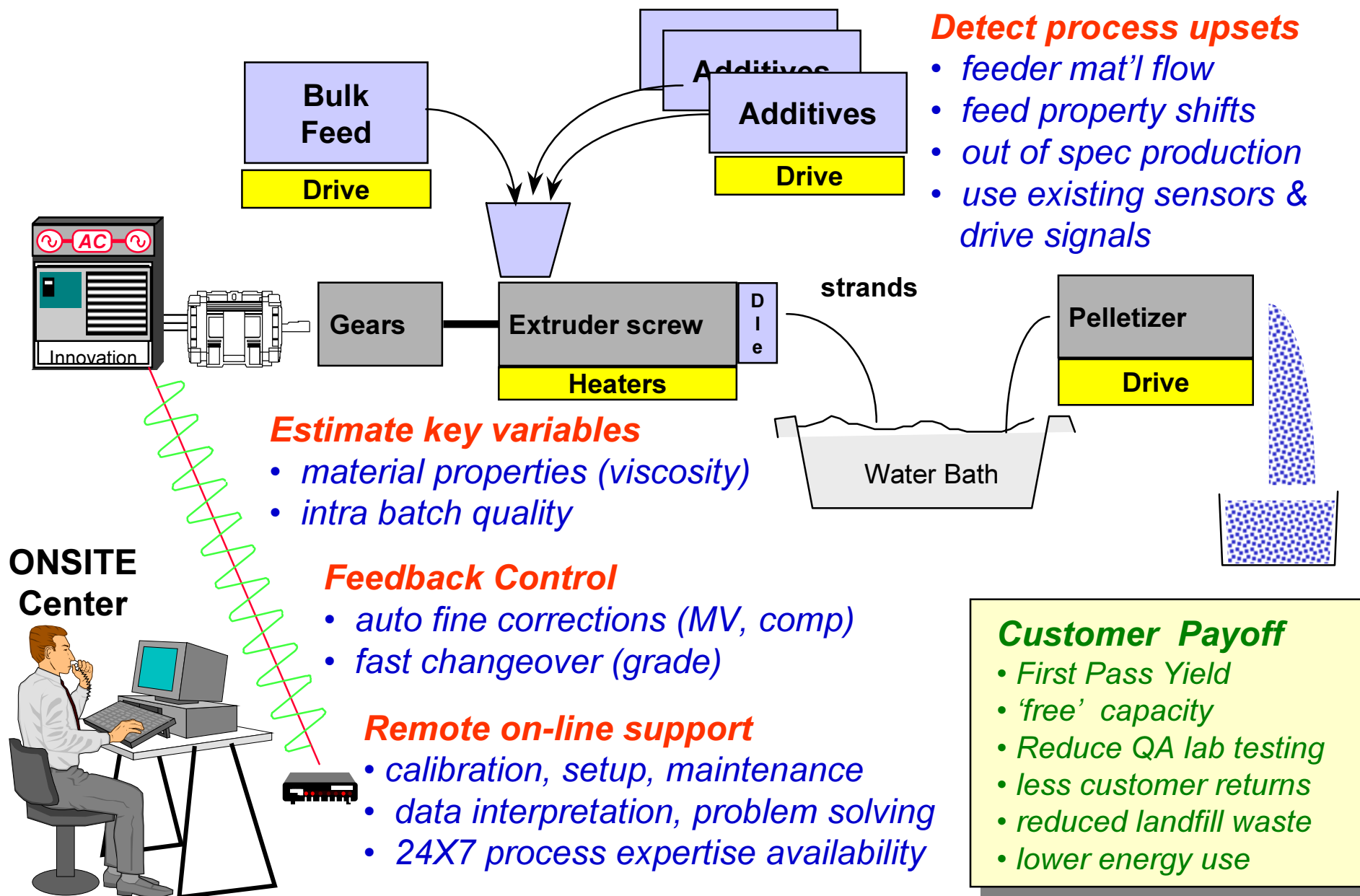
*... comments in this
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color are added to
stress key findings for
the review committee...*

Quality material the first time, every time

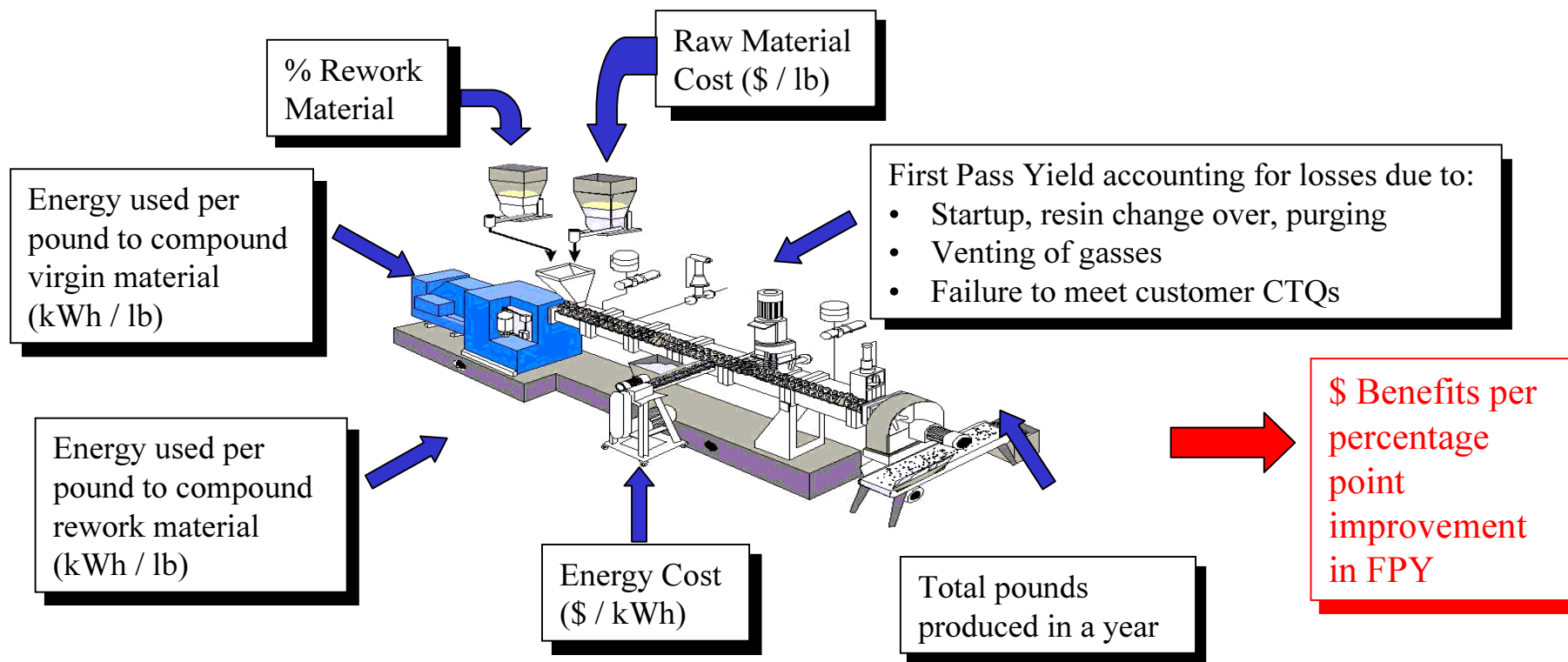
GE / Werner-Pfleiderer/ DOE Program Overview



Intelligent Extruder - Objectives



Intelligent Extruder - Benefits



Energy usage includes:

- Drives/motor for extruder, pelletizer
- Vacuum vents
- Feeders
- Barrel heaters
- Pumps

Potential benefits to improvement...

Direct (GE Plastics Noryl Example - 1998)

- **Rework: Off spec costs (\$350k/yr at 96% FPY)**
- **First Pass Yield: 3% improvement saves >\$20MM / yr**

Indirect

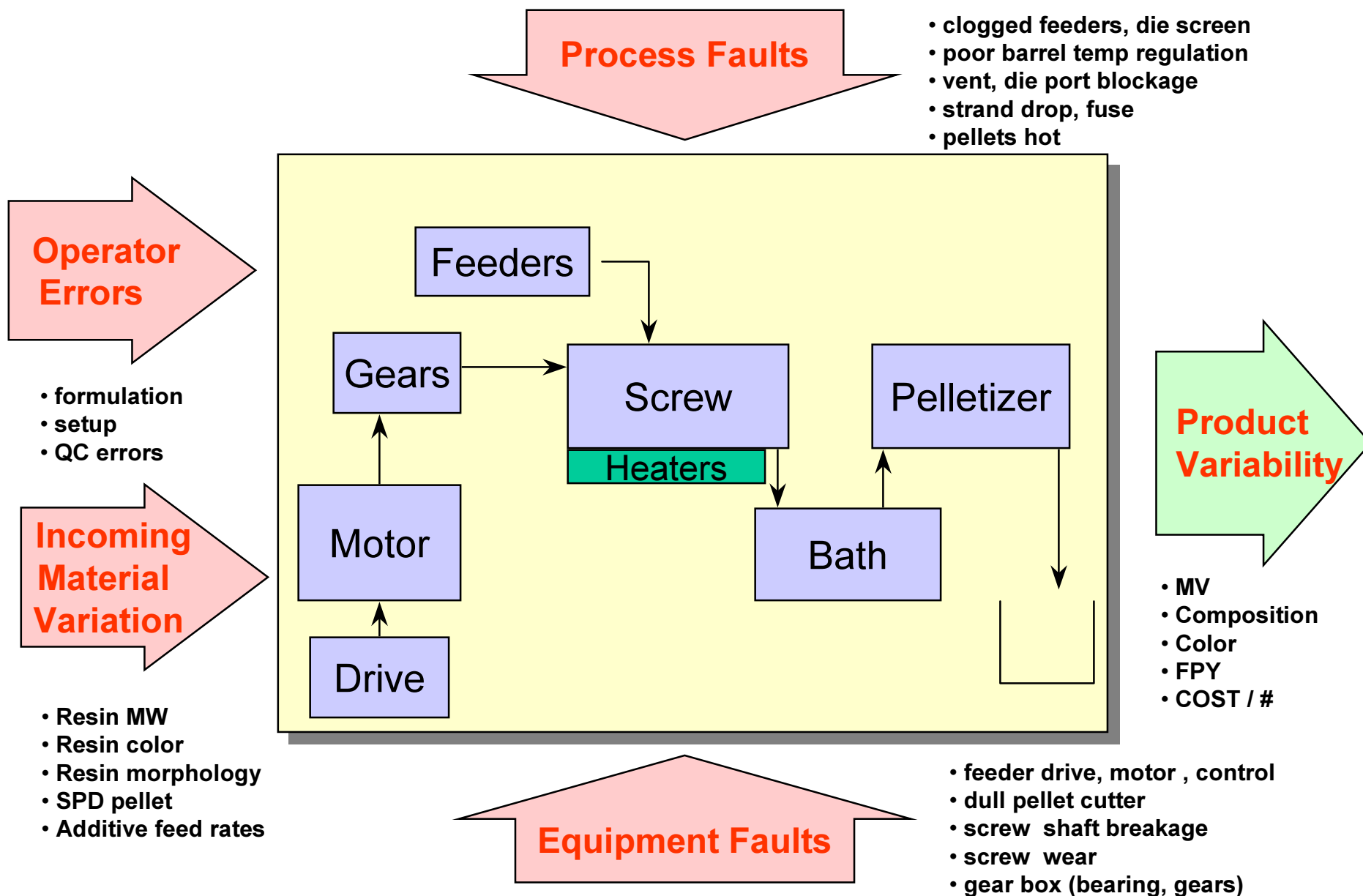
- **Reduced energy usage per lb of product**
- **Reduced customer returns impact future orders**
- **Reduced load on QA lab for offline analysis**
- **Reduced Span in JIT make to order**

What's new since 2001 OIT Review in New Orleans

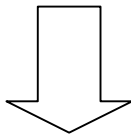
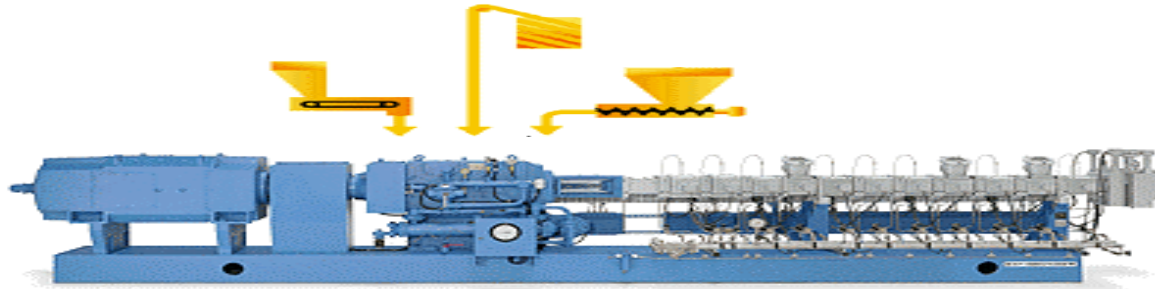
- Simplified physics-based modeling of compounding process
 - greatly simplifies parameterization of models used for diagnostics and control (fewer parameters, less on-line experiments)
- On-line identification of parameters in model
 - updated model & parameters used in estimation, diagnostics and control
- On-line estimation and feedback control system for viscosity
 - track and accommodate changes in raw materials and setpoint (grade)
- Reduced off-line rheology lab testing
 - testing for calibration once per grade/family instead of once per batch!
- Can identify and distinguish small feeder drift errors from raw material property shift for use in process upset correction
- Tested integrated diagnostics and adaptive estimation and controls on lab extruder
- Optimism for scaling to industrial production rates based on use of physics-based model

All technical objectives from original proposal have been achieved and demonstrated in the lab

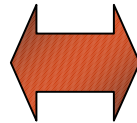
Sources of Finishing Variability



Model-Based Approach for Estimation & Diagnostics

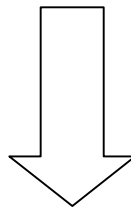


Online measurements



Physics-based dynamic model

- capture “nominal” input-output relation
- generic model structure applicable to wide range of product grades / operating conditions
- physically meaningful parameters
 - useful in fault detection/isolation

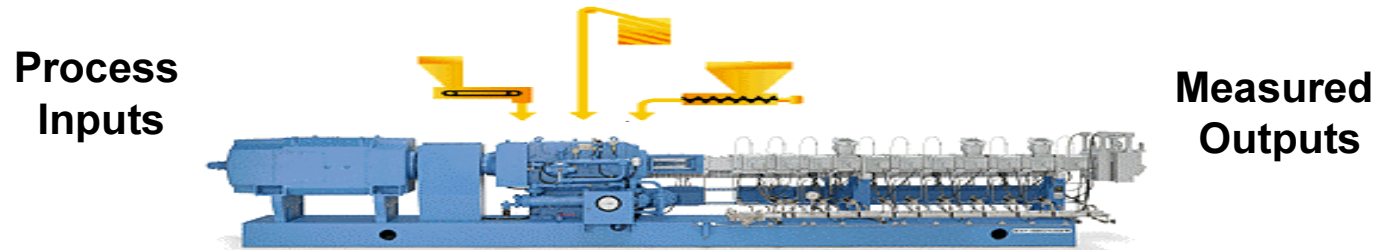


... the new model structure is key to simplifying the number of experiments and calibration runs in setting up the system

On-line estimation of product quality & process monitoring / diagnostics

- continuous online estimation of product viscosity
- detect anomalous operation and identify root cause through model-based analysis of online measurements

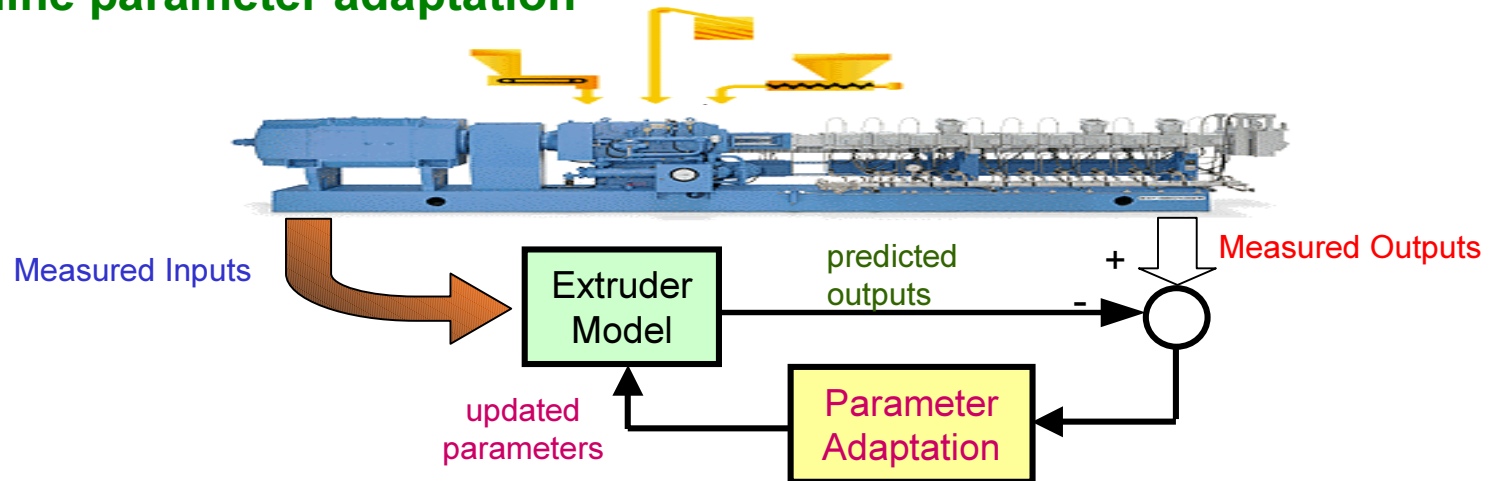
Dynamic Model for Extruder



Extruder model - capture “dynamic” relationship between inputs & outputs

- physics-based generic state-space model structure
- unknown / varying model parameters – affected by operating conditions

Use on-line parameter adaptation



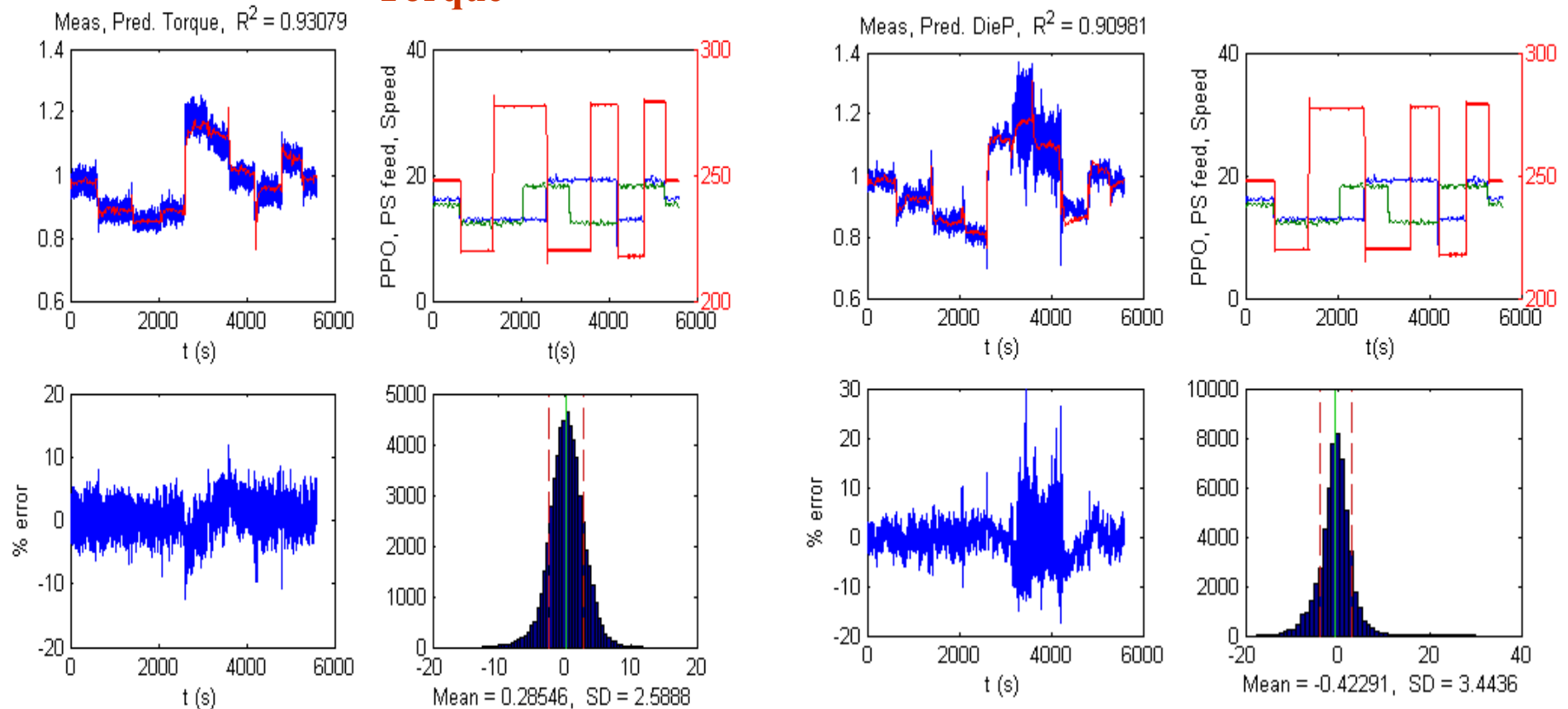
- continuously updated model with respect to changing operating conditions
- updated parameters will allow on-line estimation and diagnostics
 - exploit physical significance of model parameters

Model Fit for Torque & Die Pressure

- Data from experiment run on ZSK25 at CRD (5/08/01)
- Nominal raw materials (PPO, PS), Nominal PPO:PS ratio ($x \sim 0.52$)
- Model parameters fit to match measured torque, die pressure data

Torque

Die Pressure

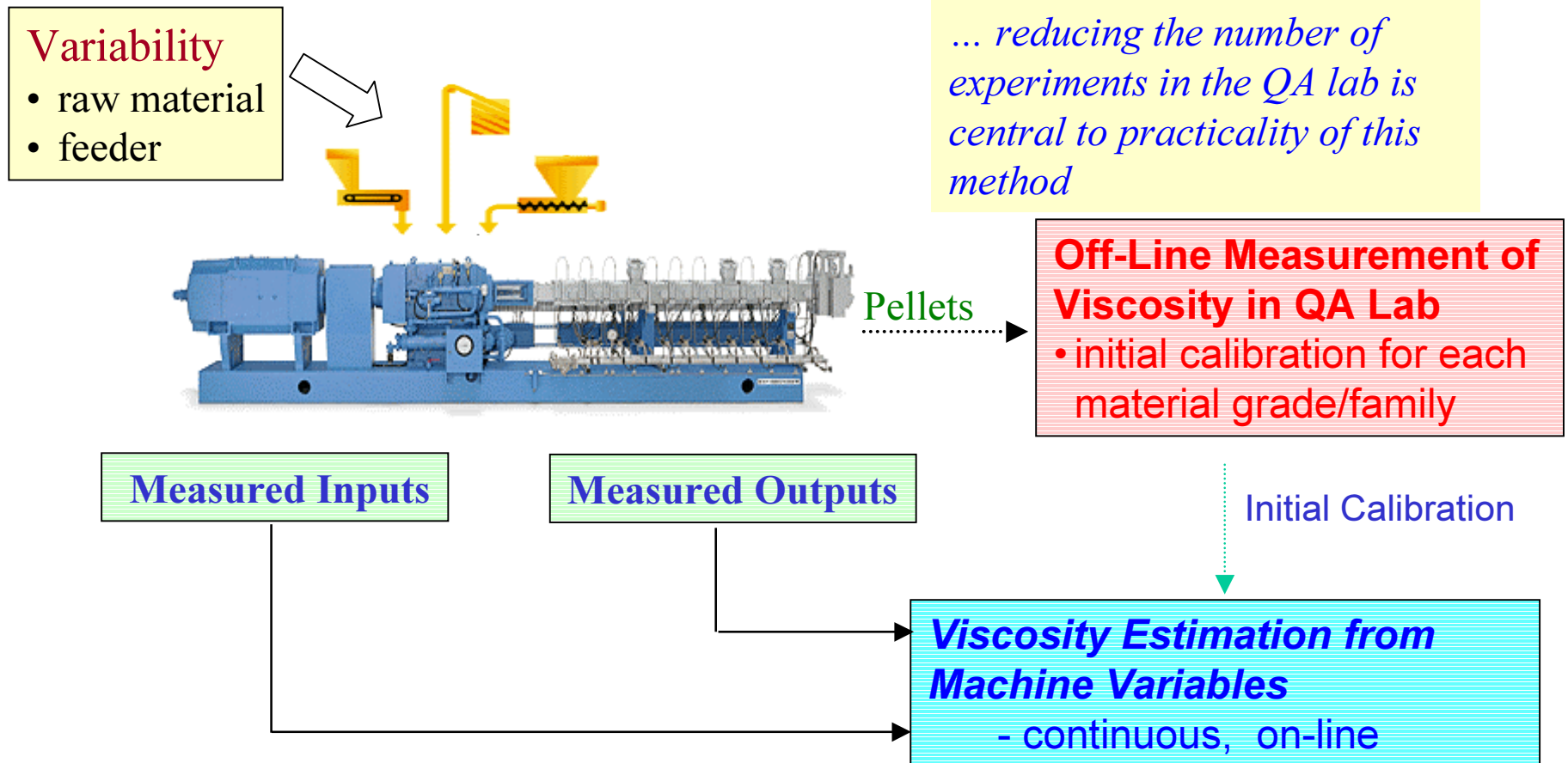


Dynamic model predicts torque & die pressure transients very well

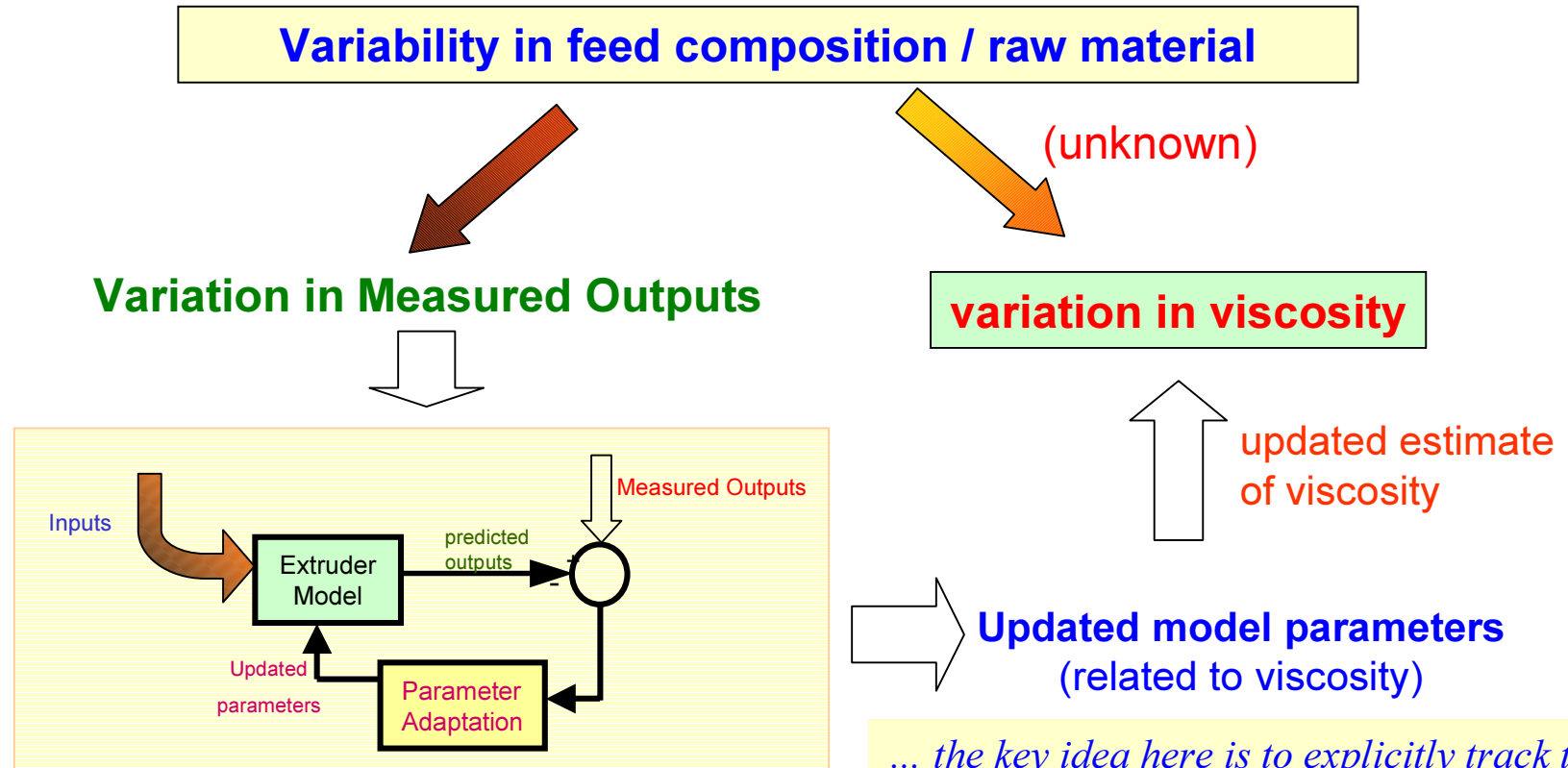
On-Line Inferential Viscosity Estimation

Why viscosity?

- key quality parameter for broad range of customers
- main cause of off-spec products (affected by raw material/composition variation)



On-Line Viscosity Estimation



... the key idea here is to explicitly track the slow variations in material property using on-line measurements to keep predictor models up to date over time...without going back to the QA lab!

Model adaptation allows continuous estimation of viscosity even under unknown variations in raw material & composition

GE CR&D ZSK-25MM Twin Screw Extruder Facility

- Capable of 1200 rpm, 164 Nm of torque, resulting in throughputs of 100 lb/hr
- Computer controlled side feeders
- Utilize K-Tron loss of weight feeders
- 30HP GE Innovation Drive

Data Acquisition Capabilities

- Monitor 24 data channels simultaneously
- Monitor barrel temperatures, barrel heater reactions, feed rates, torque, speed, die pressure, melt temperature
- Motor shaft encoder



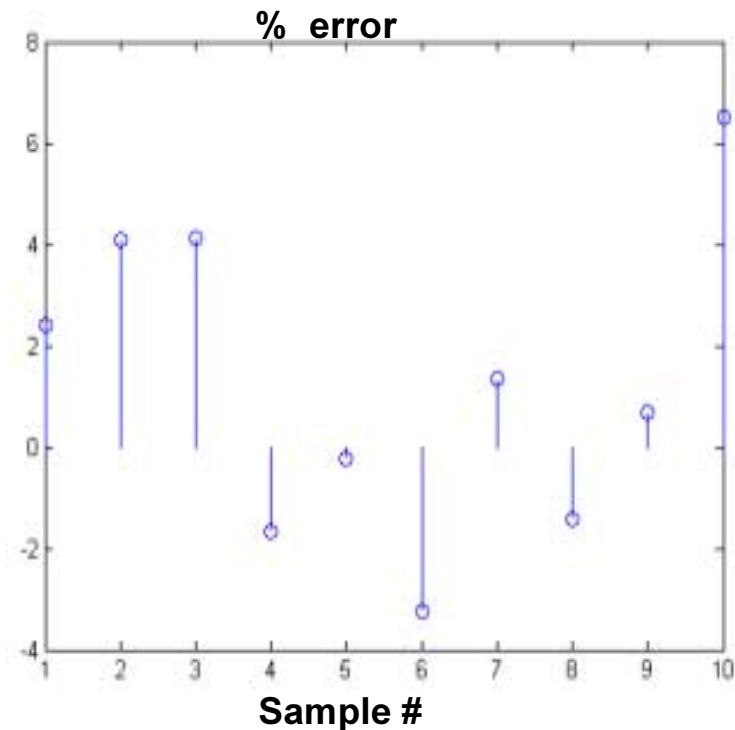
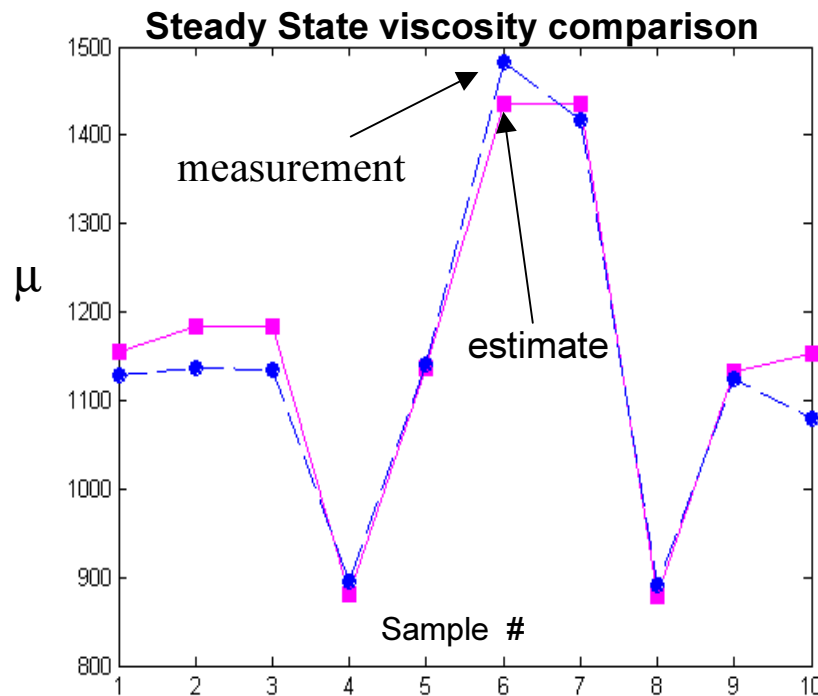
... we found that models based on this 50 lb/hr lab extruder preserved the same structure when scaled up, even though parameter values would be quite different

Procedure

- Run experiments with Noryl PX5511 (PPO+PS) at different conditions
- Collect pellet samples at steady state conditions and measure viscosity in lab (off-line)
- Compare viscosity estimated using on-line measurements with off-line lab measurements

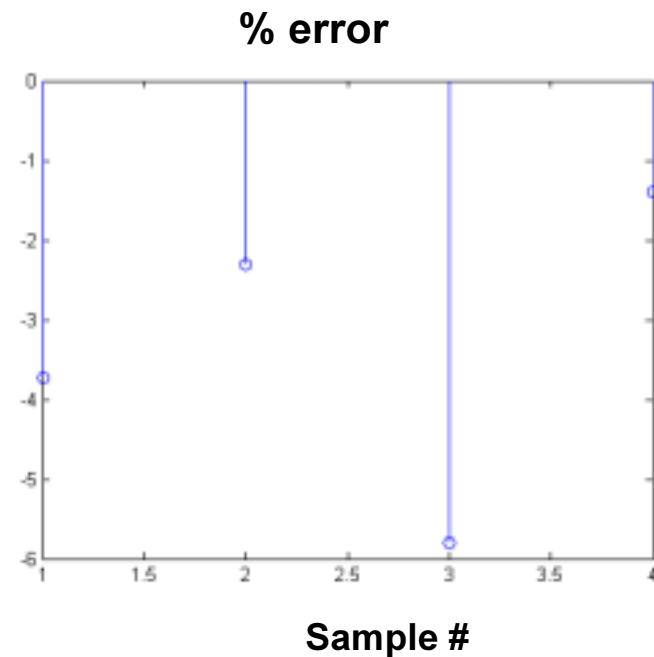
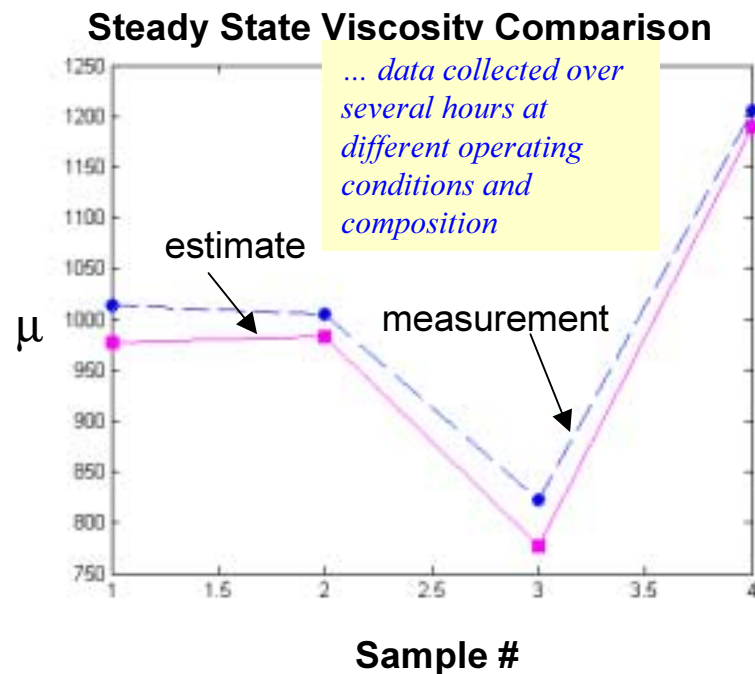
On-Line Estimation vs. Off-Line Measurement

- Experiment run on ZSK25 at CRD (5/08/01)
- **Nominal raw materials (PPO, PS)**
- **Nominal PPO:PS ratio (PPO fraction $x \sim 0.52$)**
- Off-line measurement of viscosity from 10 samples at SS conditions
- Compare off-line measurement with on-line estimation of viscosity from adapted parameters



Estimation vs. Off-Line Measurement - Change in Raw Material

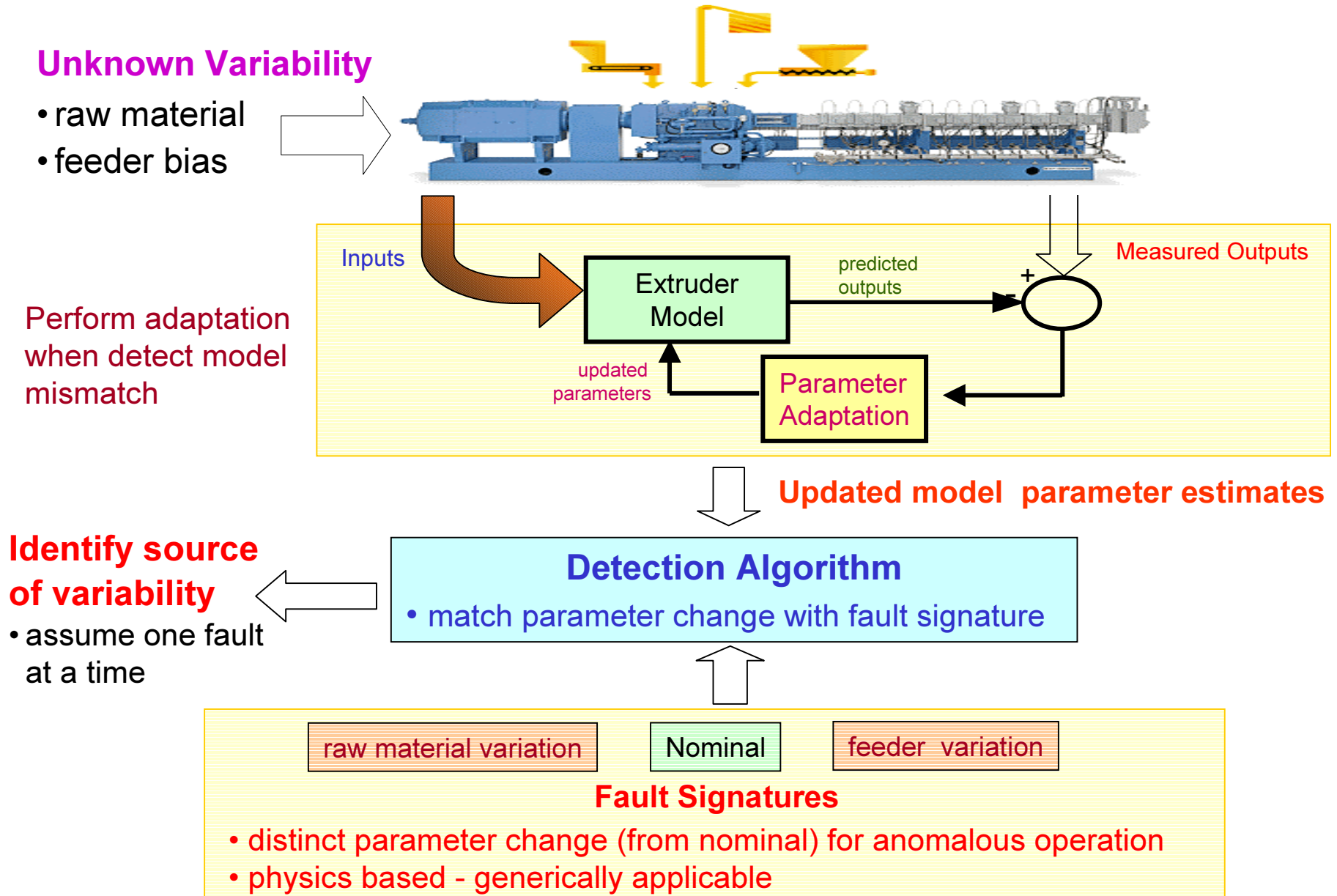
- Experiment run on ZSK25 at CR&D (10/11/01)
- **Change in raw material - medium IV PPO (mixture of .46 & .33 IV PPO)**
- **Nominal PPO:PS ratio (PPO fraction $x \sim 0.52$)**
- Off-line measurement of viscosity from 4 samples at SS conditions
- Compare off-line measurement with on-line estimate from adapted parameters



Online viscosity estimation matches well with off-line measurement



- parameter adaptation captures effect of raw material change

Model-Based Diagnostics - Approach



Results for Viscosity Estimation & Diagnostics

Goal: Test viscosity prediction stability and fault diagnosis with various anomalies

	Date of Expt	Actual Expt. Conditions	Diagnostics Result	Estimated vs. measured viscosity (μ)	Estimated slope (μ_1)
 No fault conditions	06/25/01	Nominal raw material Calibration run	Nominal	1139 (1152)	2944
	05/08/01	Nominal raw material	Nominal	1174 (1129)	2891
	05/22/01	Nominal raw material	Nominal	1167 (-)	3083
	07/25/01	Nominal raw material	Nominal	1155 (1196)	2843.5
 Fault Conditions	08/27/01	Low IV PPO	Lower IV PPO	877 (920)	2537
	10/11/01	Med IV PPO	Lower IV PPO	1002 (1010)	2550
	11/14/01	Med IV PPO	Lower IV PPO	940 (964)	2647
	12/04/01	Med IV PPO	Feeder Bias *	930 (995)	2920
	12/06/01	Med IV PPO	Lower IV PPO	968 (980)	2594
	12/14/01	Med IV PPO + unknown feeder bias*	Multiple Faults	1095 (1099) 1135**	2554 2516**

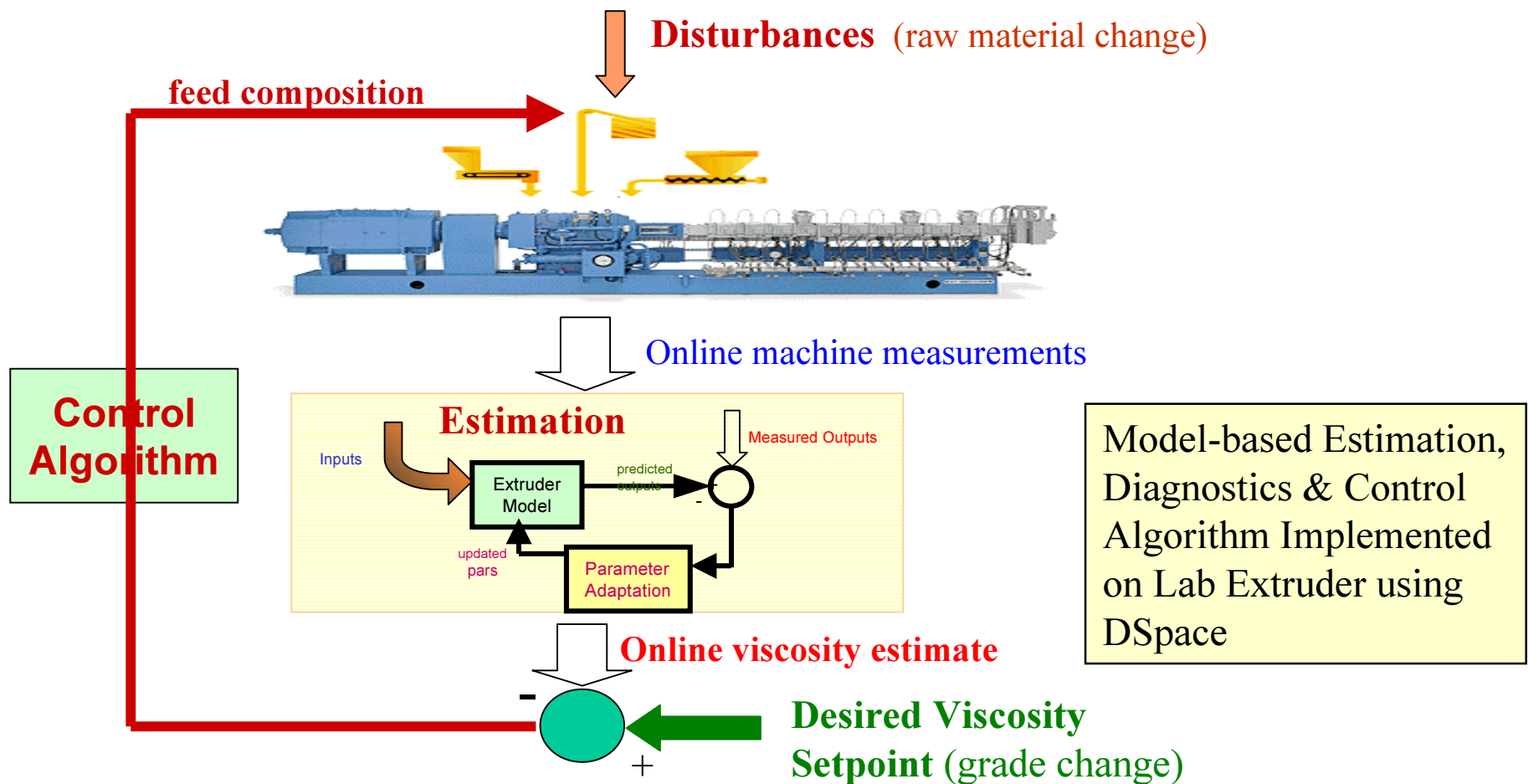
* Detect a fault but misclassify source due to multiple simultaneous faults (but estimate viscosity OK)

** Estimated after feeder bias correction

Integration of On-Line Viscosity Estimation with Closed-Loop Control

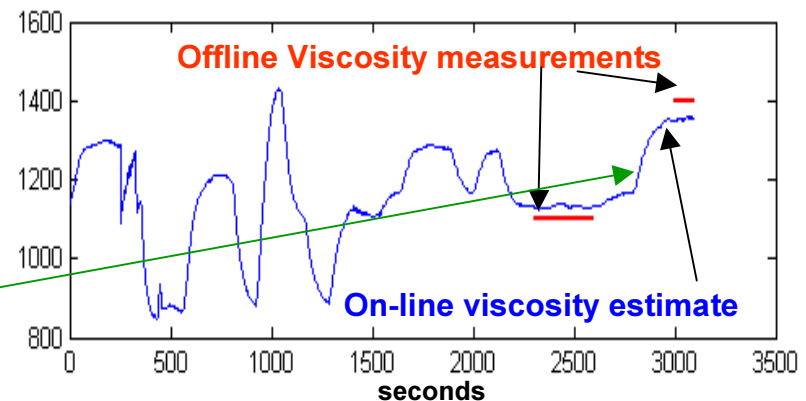
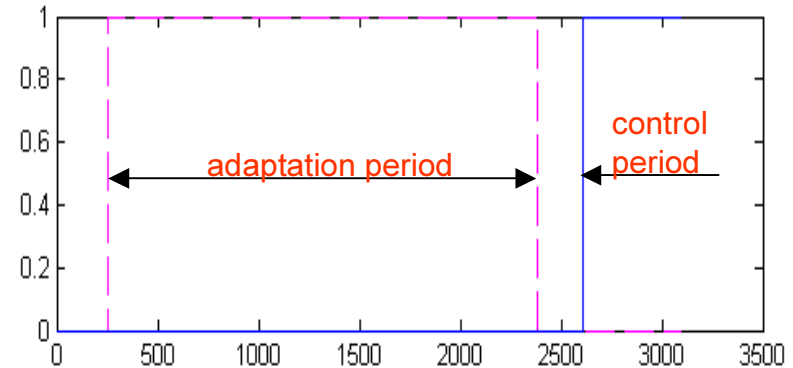
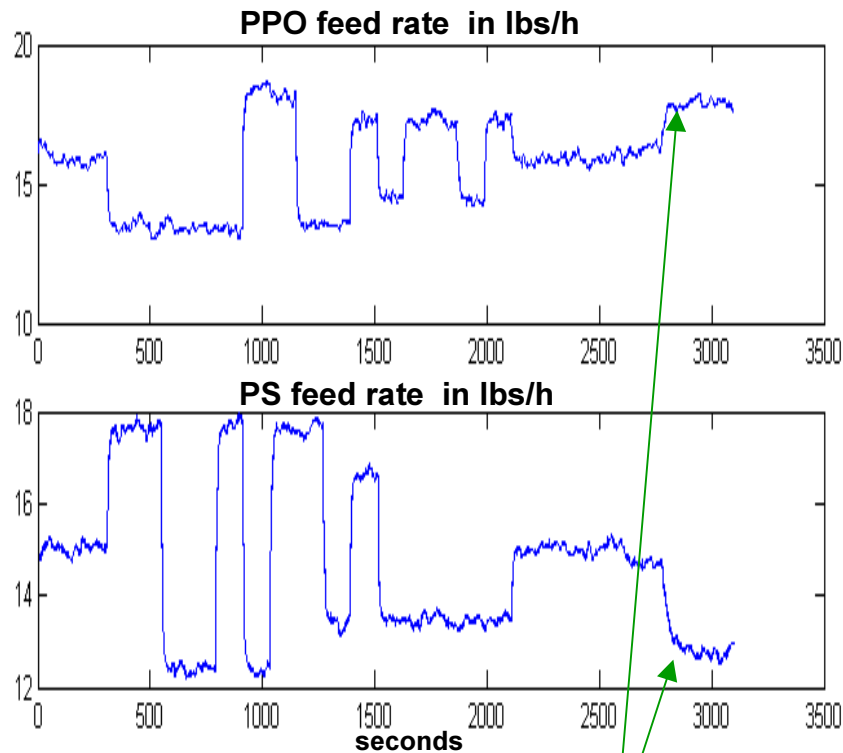
Feedback control using on-line viscosity estimate

- manipulate feed composition as control input
- track changing viscosity setpoint (grade transition)
- reject effect of unknown disturbances (raw material variation)



Expt Demo of On-Line Viscosity Estimation & Closed-Loop Control

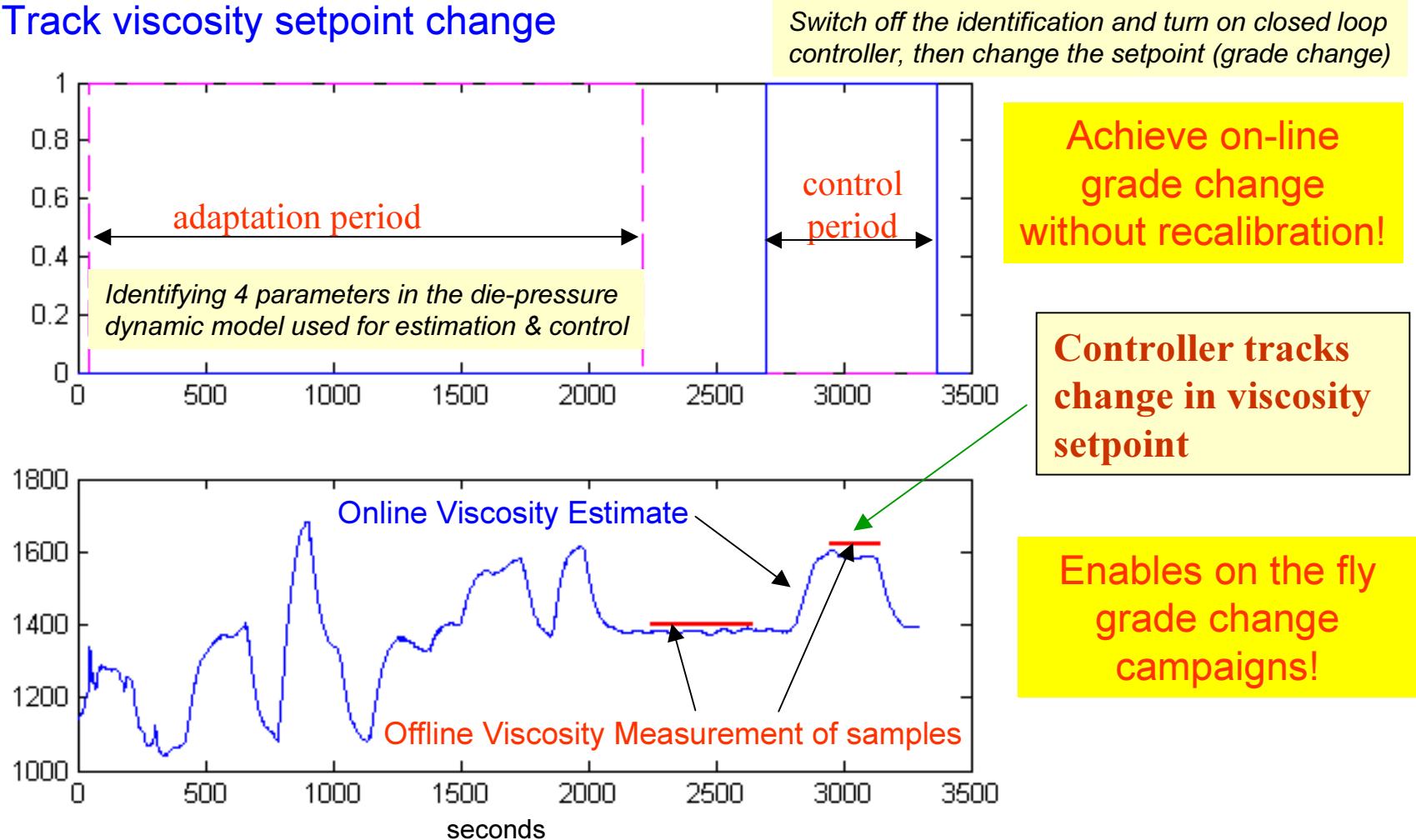
- Experiment run on ZSK25 at CRD (12/14/01)
- **Change in raw material (med. IV PPO), High PPO fraction ($x \sim 0.57$)**
- Adapt model parameters & update viscosity estimate
- Relect effect of raw material change (disturbance)



Controller compensates for raw material change (lower IV PPO) by changing feed ratio to get viscosity on target

Expt Demo of On-Line Viscosity Estimation & Closed-Loop Control

- Experiment run for calibration on ZSK25 at CRD (12/14/01)
- **Nominal raw materials, High PPO fraction** (ratio ~ 0.57)
- Adapt model parameters & update viscosity estimate
- Track viscosity setpoint change





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Intelligent Extruder Summary

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- Tested integrated diagnostics, adaptive estimation and controls on lab extruder
- Optimism for scaling to industrial production rates based on use of physics-based model
- Plan for scale-up at GEP, WP, commercialization with GEIS

*More Information
(see handout)
or contact*

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